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Tracking and Control of Gas Turbine Engine Component Damage/Life

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ABSTRACT

This paper describes damage mechanisms and the methods of controlling damages to extend the on-wing life of critical gas turbine engine components. Particularly, two types of damage mechanisms are discussed: creep/rupture and thermo-mechanical fatigue. To control these damages and extend the life of engine hot-section components, we have investigated two methodologies to be implemented as additional control logic for the on-board electronic control unit. This new logic, the life-extending control (LEC), interacts with the engine control and monitoring unit and modifies the fuel flow to reduce component damages in a flight mission. The LEC methodologies were demonstrated in a real-time, hardware-in-the-loop simulation. The results show that LEC is not only a new paradigm for engine control design, but also a promising technology for extending the service life of engine components, hence reducing the life cycle cost of the engine.

1. Introduction

Gas turbine engines consist of primarily rotating components. These rotating components operate under cyclic loading condition and harsh environment (i.e., under high temperature, pressure, corrosion condition) such that the deterioration of these components is accelerated. Deterioration is generally tracked by damages, or damage rates, for different damage mechanisms. The most common damage mechanisms for a gas turbine engine include: low cycle fatigue (LCF), thermo-mechanical fatigue (TMF), high cycle fatigue (HCF), creep, rupture, corrosion, and foreign object-induced damages (FOD). Of these common damage mechanisms, LCF and HCF are primarily design issues; FOD and corrosion are ambient-condition driven; hence TMF, creep, and rupture are the prime candidates for damage control and life extension on a continuous-operation basis.

TMF, creep, and rupture have similar damage patters. The simplest patter is where the damage rate (d) is geometrically proportional to a key engine operating parameter (x), sometimes called a damage driver, as shown in Figure 1. To analyze damage mechanisms more accurately, we often consider additional damage drivers. Additional damage drivers reveal more complex damage patterns as shown in Figures 2 and 3.

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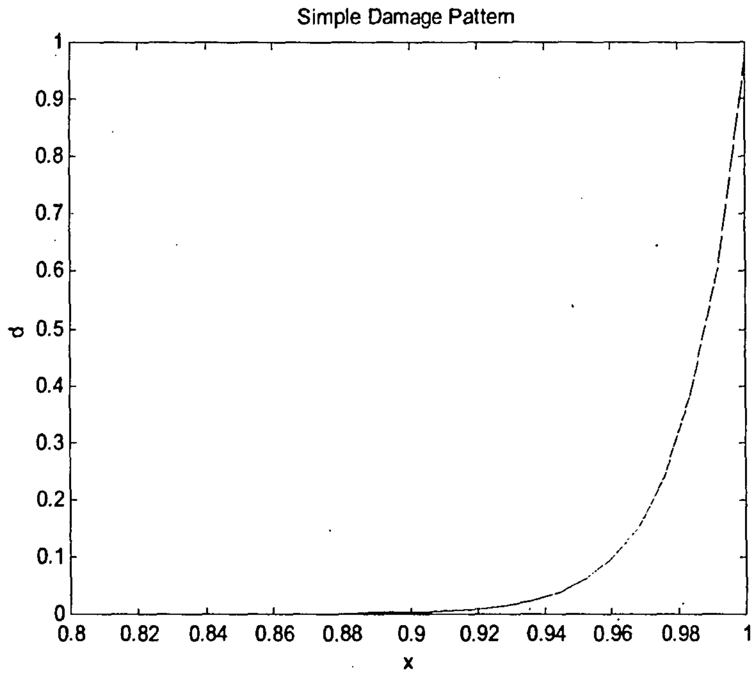

Figure 1: A simple damage pattern

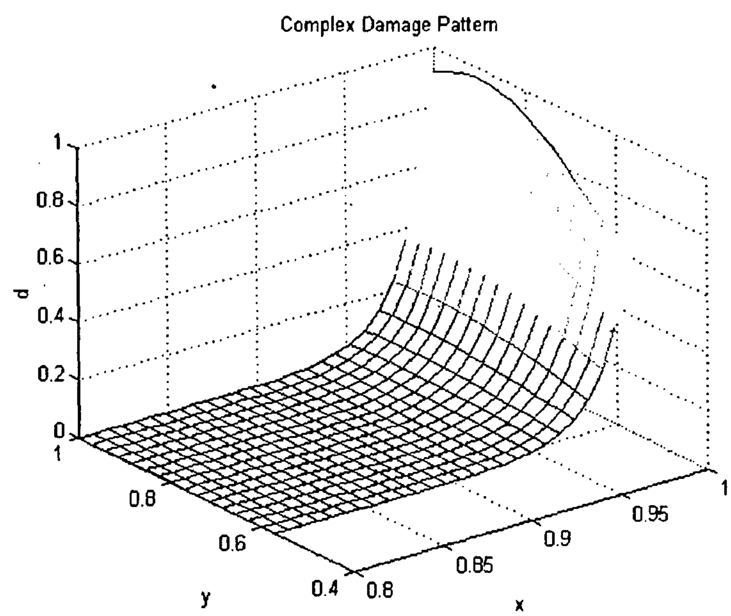

Figure 2: A complex damage patterns

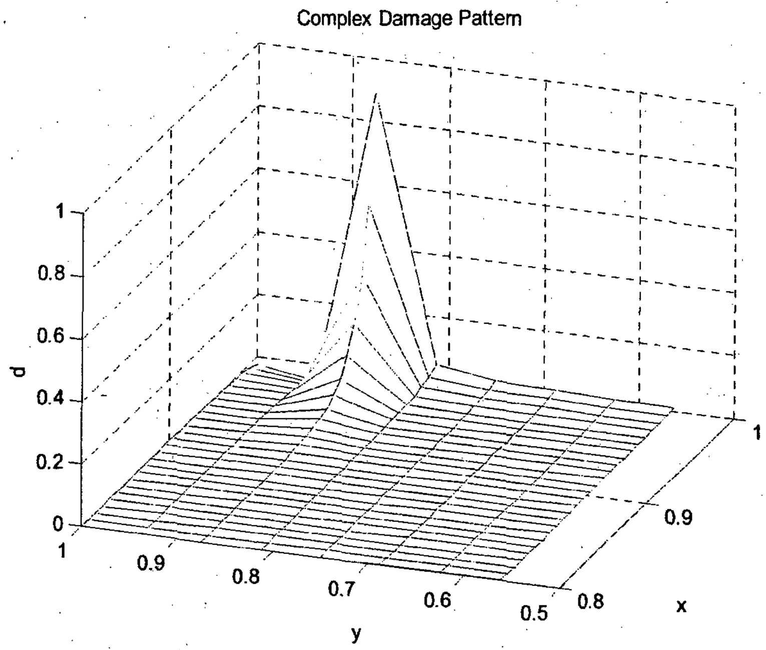

Figure 3: Another damage pattern

Generally speaking, the approaches to controlling the damage and extending component life fall into two categories:

- *Active* control: changing the operating procedures pertaining to mission planning or engine control, and tracking the damage concurrently[1].
- *Passive* control: tracking damages and adjusting maintenance practices to maximize the utilization of the service life of a component.

This paper concerns with the active control approach, specifically, extending the life of hot-section components through active engine control of TMF, creep, and rupture damages. This approach is called life-extending control (LEC). The LEC concept originates from damage mitigating control research for rocket engines [1-5]. It controls engine fuel flow rate by including damage-reduction as an active objective. The differences between a liquid-fueled rocket engine and a gas turbine engine are summarized as follows: 1) a rocket engine has a narrow operating envelope, its mission profile is mostly fixed; 2) a rocket engine has much shorter firing durations; 3) a rocket engine has much longer down time for each mission cycle; 4) a rocket engine has no air breathing provision, hence, not susceptible to contamination and corrosion.

The challenge of LEC is to maintain satisfactory levels of performance and operability while reducing component damages. To meet this challenge, LEC is preferably designed to trim the standard engine control logic with a limited authority.

This paper describes two methodologies to reduce the life cycle cost of gas turbine engines. The first methodology reduces stress rupture/creep damage to turbine blades and stators by optimizing damage accumulation concurrently with the flight mission. This methodology is

[1] By concurrent tracking of damages we mean the time from feeding damage information back to mission planning or engine control is much shorter compared with this feedback process in the passive control approach.

described in Section 2. The second methodology modifies the baseline control logic of an engine to reduce the TMF damage of cooled stators during acceleration. This methodology is described in Section 3. These methodologies have also been implemented in an actual full-authority digital electronic control (FADEC) unit of a small gas turbine engine to demonstrate the feasibility of LEC. A real-time, hardware-in-the-loop (HITL) simulation has also been conducted as a part of the feasibility demonstration. Section 4 describes the HITL simulation.

2. Stress Rupture/Creep Damage Reduction

A typical flight mission of an aircraft consists of taxi, take-off, climb, cruise, descent and landing. In this section, we describe the reduction of rupture damage during a specific portion of a flight mission: cruise. Since a civil airplane flies most of the time at the cruise condition, reducing engine component damages during cruise will directly increase the service life of the engine components.

Generally speaking, increasing cruise speed reduces flight time but increases the thrust requirement. This implies higher engine speed and temperature hence high damage rate to the turbine blades and stators. Therefore, there is trade-off among flight time, fuel cost, and accumulated component damages during cruise. An optimization to perform this trade-off among flight time, fuel cost, and accumulated engine component damages during cruise was formulated and is shown in the Figure 4 below.

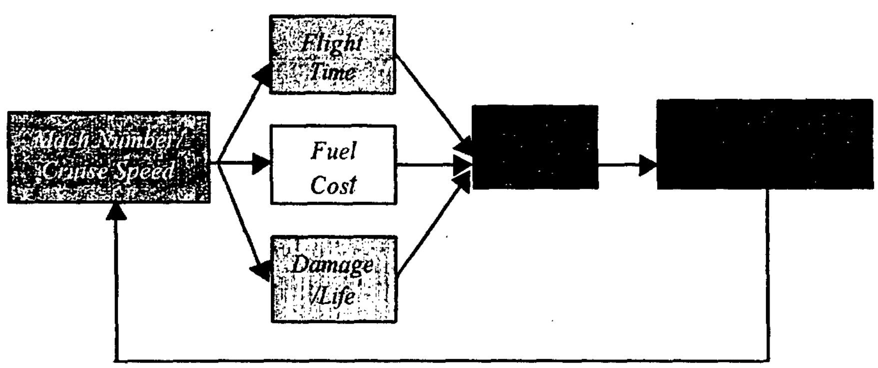

Figure 4: A trade-off between performance and rupture/creep damage in cruise conditions

<u>Flight Mission</u>

A business jet is used to demonstrate this trade-off optimization concept. A typical flight mission of this type of airplane is shown in Figure 5. There are three cruise segments in the flight mission. The first cruise segment is at altitude 41000ft, the second cruise segment is at altitude 43,000ft, and the third cruise segment is at altitude 45,000ft. The Mach number for all three cruise segments is 0.8.

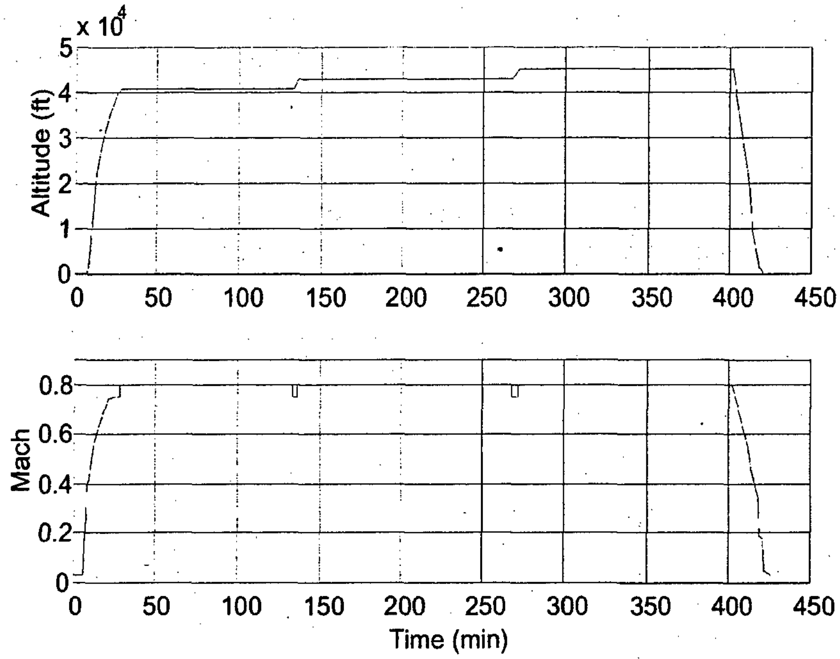

Figure 5: A typical flight mission of the business jet

Aircraft Model

From the equations of motion of an aircraft in level flight, the required engine thrust in cruise condition can be determined from the following two equations:

$$T = \tfrac{1}{2}\rho S C_d V^2 \tag{1}$$

$$mg = \tfrac{1}{2}\rho S C_l V^2 \tag{2}$$

where ρ the density of the air, S the reference area of the aircraft, C_d the drag coefficient, C_l the lift coefficient, V is the cruise speed.

The relationship between C_d and C_l is described by the drag-polar equation:

$$C_d = C_{d0} + \beta C_l^2 \tag{3}$$

where the zero-lift drag coefficient C_{d0} and the induce drag factor β are functions of Mach number only.

The thrust T, as a function of cruise speed and mass of aircraft, can be written as

$$T = \tfrac{1}{2}\rho S C_{d0} V^2 + 2\beta \frac{m^2 g^2}{\rho S V^2} \tag{4}$$

Cumulative Damage In Cruise

Based on the required thrust determined by Eq. (4), cumulative component damages during cruise are determined by using the damage model. For the first cruise segment of the mission profile (altitude 41000ft, cruise speed 0.8 Mach, cruise time 105 min), Figures 6 to Figure 8

show the cumulative damages for blades and stators. Figure 9 shows the total fuel consumption as a function of cruise Mach number and initial weight with respect to a reference initial weight $m_0 g$.

It can be seen from these figures that the cumulative component damage during cruise increases exponentially with respect to the Mach number. Large damage reduction can be achieved with very small sacrifice in flight time. Total fuel consumption during cruise.

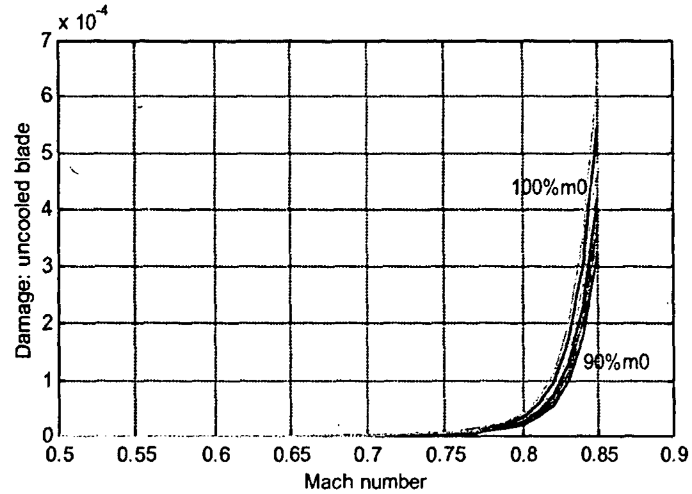

Figure 6: Cumulative damage of un-cooled blade during cruise

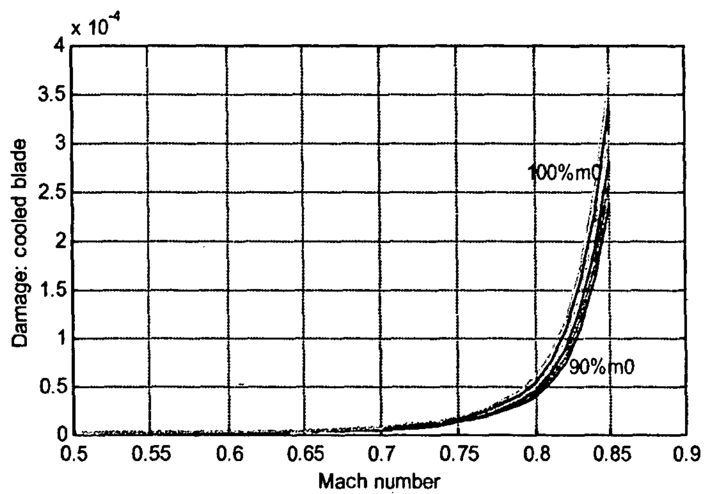

Figure 7: Cumulative damage of cooled blade during cruise

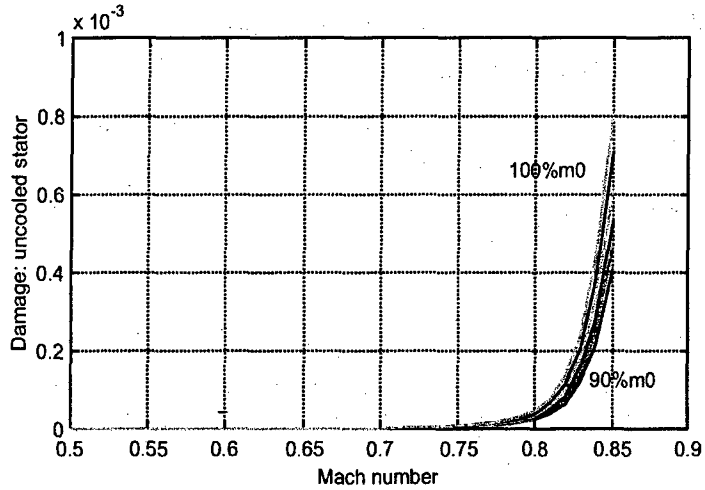

Figure 8: Cumulative damage of un-cooled stator during cruise

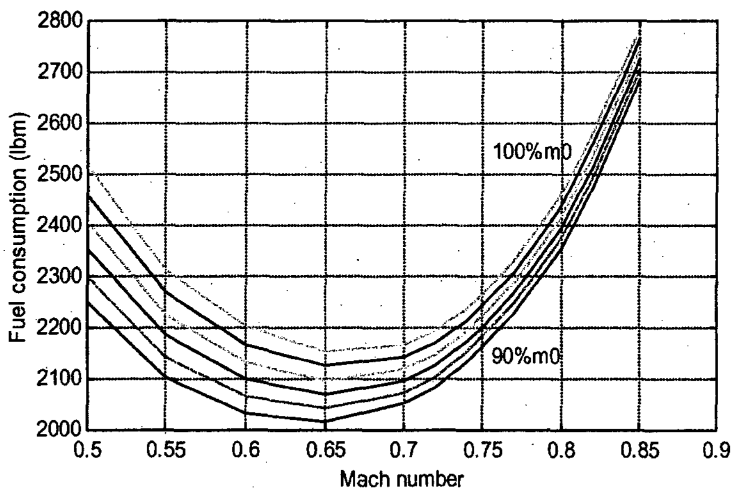

Figure 9: Fuel consumption during cruise

Trade-off Optimization

To demonstrate this optimization approach, a linear objective function of flight time, fuel consumption and cumulative damage is formulated as follows:

$$J = \alpha_1 \frac{t_f}{t_{f\_ref}} + \alpha_2 \frac{D_1}{D_{1\_ref}} + \alpha_3 \frac{D_2}{D_{2\_ref}} + \alpha_4 \frac{D_3}{D_{3\_ref}} + \alpha_5 \frac{WF}{WF_{ref}} \qquad (5)$$

where

t_f: Cruise time

t_{f_ref}: Cruise time at a nominal cruise Mach number

D_1: Cumulative damage for uncooled blade

D_{1_ref}: Cumulative damage for uncooled blade at a nominal cruise Mach number

D_2: Cumulative damage for cooled blade

D_{2_ref} : Cumulative damage for uncooled blade at a nominal cruise Mach number

D_3 : Cumulative damage for cooled stator

D_{3_ref} : Cumulative damage for uncooled stator at a nominal cruise Mach number

WF : Total fuel consumption during cruise

WF_{ref} : Total fuel consumption during cruise at a nominal cruise Mach number

α_i : Weighting coefficients

Assume $\alpha_1 = 10$, $\alpha_2 = \alpha_3 = \alpha_4 = 1/3$, $\alpha_5 = 1$. For different reference cruise Mach number 0.70, 0.75, 0.80, Table 1 below lists the optimal Mach number, the damages at the optimal cruise Mach number divided by the damages at the reference cruise Mach number, and the fuel consumption at the optimal cruise Mach number divided by the fuel consumption at the reference cruise Mach number, for three reference Mach numbers.

Note that the objective function reaches its minimum at the reference cruise Mach number for the reference Mach number below 0.70. This is caused by the large weighting on the cruise time in the objective function. The objective function at different Mach number for the reference Mach number 0.8 is shown in Figure 10. For the Mach numbers greater than 0.75, more reduction in Cumulative damages can be achieved with small reduction in cruise speed.

Table 1: Optimization results

Ref. Mach	Optimal Mach	D_1/D_{1_ref}	D_2/D_{2_ref}	D_3/D_{3_ref}	F/F_{ref}
0.70	0.70	1.0	1.0	1.0	1.0
0.75	0.72	0.43	0.58	0.41	0.96
0.80	0.77	0.32	0.48	0.30	0.94

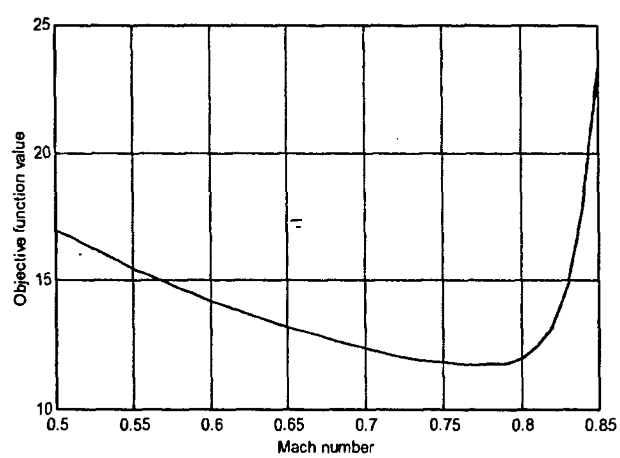

Figure 10: Objective function value at different cruise Mach number

3. TMF Damage Reduction

The actual engine control logic has been modified to reduce the TMF damage during engine acceleration from ground idle to maximum power. The goal is to reduce the TMF damage while maintaining fast engine acceleration. Several approaches to modifying engine control logic have been investigated including: target speed offset, control gain increase/decrease and acceleration schedule reduction. It was found from engine simulation that acceleration schedule reduction is the most effective.

In a typical turbine engine control, engine acceleration follows an acceleration schedule; specifically, the engine speed is controlled to follow the acceleration schedule. To reduce TMF damage, the acceleration schedule was reduced by a certain percentage once the difference between the controlled speed, high pressure spool speed (NH) and the target speed is less than a threshold. This is illustrated in Figure 11 below.

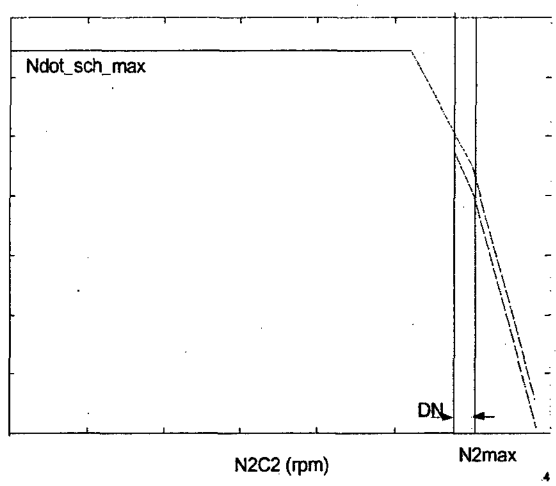

Figure 11: Illustration of acceleration schedule reduction logic

For the threshold values (DN) of 800 rpm, 1000 rpm, and 1200 rpm, the reductions in TMF damage (in percentage) and the increase of rise time of fan speed (N1) (an indicator of engine thrust) during the engine acceleration from ground idle to maximum power are shown in Tables 2 to Table 4, and in Figure 12 and Figure 13 for 50% to 90% reduction of the acceleration schedule. It can be seen that the greater the reduction of TMF damage, the greater the increase in rise time. It is also found that the relationship between the TMF damage reduction and increase in rise time is not sensitive to the threshold values. For all three cases, significant reductions in TMF damage can be achieved with only a very small increase in rise time for N1 and thrust.

Table 2: TMF damage reduction for DN=800 rpm

%, reduction	TMF reduction (%)	Extra rise time (sec)
10%	13.7	0.06
20%	24.5	0.12
30%	35.3	0.22
40%	45.6	0.32
50%	49.0	0.58

Table 4: TMF damage reduction for DN=1000 rpm

%, reduction	TMF reduction (%)	Extra rise time (sec)
10%	14.7	0.06
20%	26.4	0.16
30%	37.7	0.28
40%	47.5	0.40
50%	54.3	0.74

Table 5: TMF damage reduction for DN=1200 rpm

%, reduction	TMF reduction (%)	Extra rise time (sec)
10%	14.7	0.08
20%	27.5	0.18
30%	39.2	0.32
40%	49.0	0.50
50%	56.9	0.86

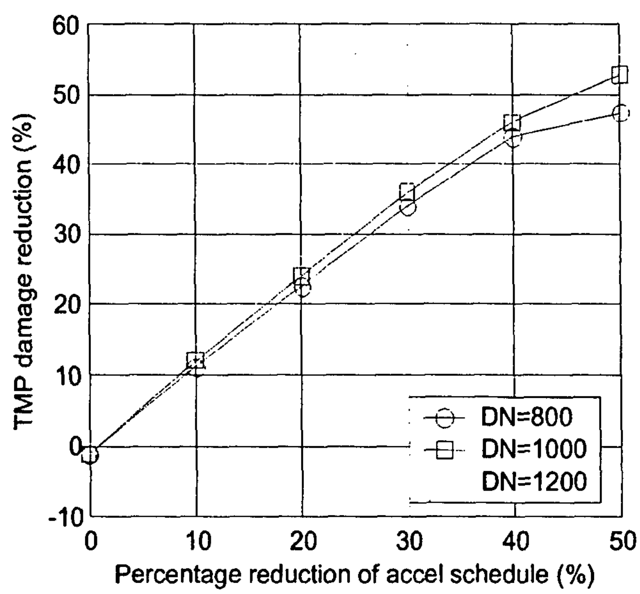

Figure 12: TMF reduction vs. reduction of acceleration schedule vs. speed threshold

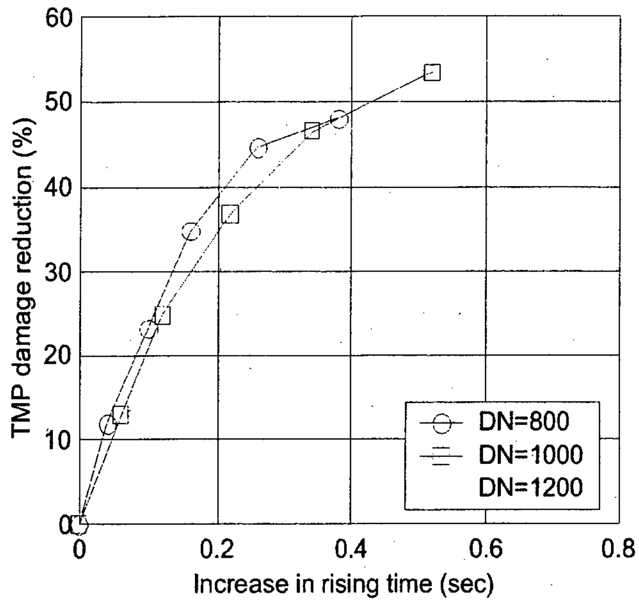

Figure 13: TMF reduction vs. increase in rise time vs. speed threshold

4. Hardware-in-the-loop Simulation

The methodologies have been implemented in an actual full-authority digital electronic control (FADEC) unit of a small gas turbine engine to demonstrate the feasibility of LEC. Real-time, hardware-in-the-loop simulations have been conducted and verified the LEC concept through the two life extension methodologies. Figure 14 shows the simulation environment and a data screen.

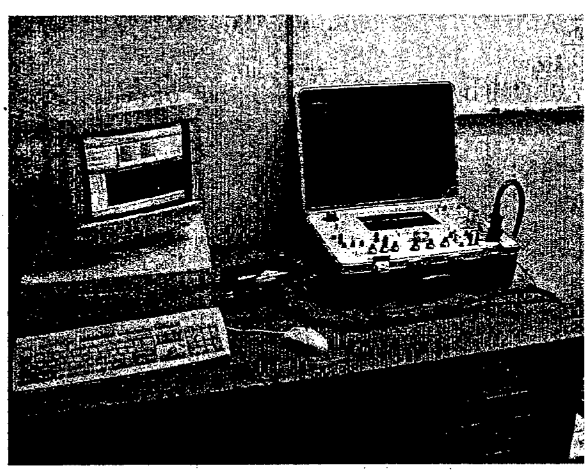

Figure 14a: HITL simulation setup

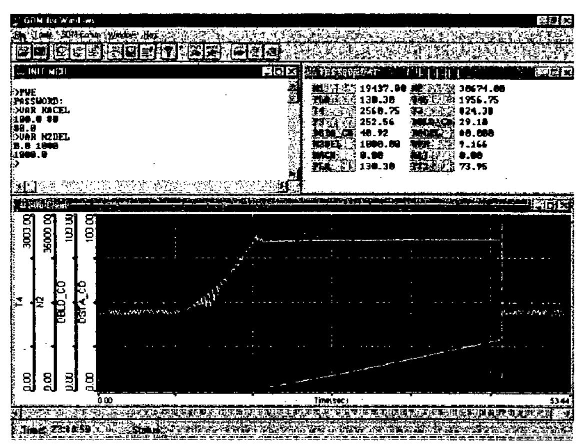

Figure 14b: real-time data display

5. Conclusions

This paper describes two methodologies to extend the service life of hot-section components, particularly, turbine blades and stators, by reducing the damages incurred on these components. One methodology has been designed to reduce the creep damage in cruise. The other methodology has been designed to reduce the thermo-mechanical fatigue damage in rapid transients. These methodologies for damage reduction and life extension have been evaluated for a small commercial turbine engine for a general aviation aircraft. Evaluation was performed by hardware-in-the-loop simulations where an actual engine full-authority digital electronic control (FADEC) unit was modified with the LEC, and it interacted with an engine simulator in real time. The results of this evaluation show that significant reductions in these damages are promising and the design for life extension could be considered in engine control systems. The team anticipates to substantiate the analytical results by carefully designed experiments and engine testing in the next phase of the program.

6. Acknowledgment

The authors want to thank Dr. Ten-Hui Guo of NASA Glenn Research Center and Mr. Robert S. McCarty of Honeywell Engines and Systems for their support during the course of this three-year program. The financial support from NASA and the generous support of technical information by Honeywell are essential for the success of this program.

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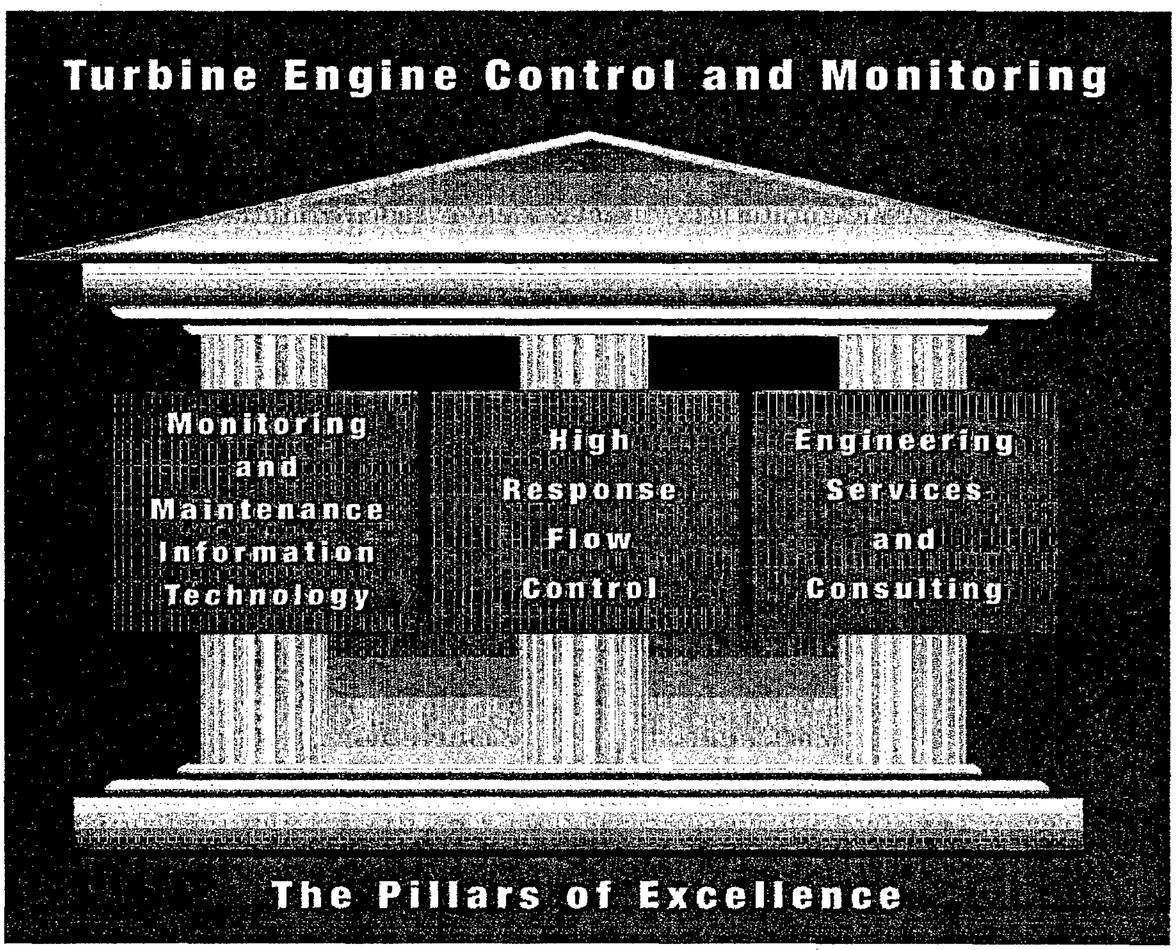
Link Jaw founded Scientific Monitoring, Inc. (SMI) in 1993. He has been involved in all aspects of corporate management including projects, strategies and resources. Link has over 25 years of experience in engineering, software, and management. Prior to starting SMI, he worked for AlliedSignal Aerospace, Link Flight Simulation, and FlightSafety Simulation. Link is the inventor of five U.S. patents. He holds an M. S. degree from the University of Michigan and a Ph. D. degree from Stanford University. He also completed executive management training at the Tuck School of Business Administration of Dartmouth College.



Paper 12: Discussion

Question from H Pfoertner – MTU, Germany

Creep life usage is heavily dependent on temperature. Does the cruise segment, as considered in your analysis, really contribute a significant percentage of total creep damage?

Is it necessary to change the control laws to change cruise speeds, surely that could be readily achieved by the pilot?

Presenter's Reply

Your comment on cycle-independence for creep and rupture damage is correct; these types of damage depend mostly on temperature and pressure.

Of course, it is possible for the pilot to set the cruise speed but the pilot requires some instructions from a flight management or mission computer to know the required setting. To make optimised recommendations, such computers require inputs of usage tracking information from a controller or diagnostic unit like the one described.